Modal identification of a flexible footbridge using output-only methods

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Abstract

This work researches the modal frequencies identification of a footbridge structure by output only technique. The structural system of the footbridge herein considered is a continuous curved girder, i.e. belongs to a frequently used one all around the world in urbanized areas. It is located on the Princeton University campus in the US and serves as an on-site laboratory for short- and long-term research and educational purposes.
The investigation utilizes measurements collected by long-gauge fiber optic strain sensors installed along the main-span and south-east leg of the structure. The power spectral density of the distributed long-gauge dynamic strain response in terms of curvature is used for detecting the modal frequencies of the footbridge. Pedestrian loading represents the external excitation. However, detailed information on the load intensity, frequency and distribution are lacking. This aspect represents the challenge of the present research with the aim to obtain as much information as possible about the modal characteristics of the footbridge from very limited dynamic information (only on the structural response) and without knowing the input conditions. Previously published research serves as a guide for evaluating the effectiveness of the results and the effectiveness of the employed methodology.
This preliminary step paves the path to further research, i.e., (i) to the implementation of a refined finite element model of the entire structure for dynamic analysis, and (ii) to the development of a new wireless sensor network, by using as a reference the results from the existing embedded fiber optic sensors.

1. Introduction

Information on the structural condition and safety can be gained through the analysis of the structural parameters collected by monitoring systems and processed by suitable methods. This activity is usually termed as structural health monitoring (SHM) and can be divided in four main phases, from the essential *assessment of presence of damage* to the most complicated *prognosis* of the structural state and remaining life. *Localization* and *quantification* of damage are the intermediate phases.
SHM is also connected to the innovative view of resilience for civil structures and infrastructure that is attracting the attention of several specialists all over the world, particularly in the bridge engineering field. The time required to recover the original performance of structure after a damaging event, is the crucial resilience aspect to be investigated. The capacity to assess damage presence, localization and intensity is obviously essential for developing resilient structures and communities.

The exclusive use of structural response variables for the system parameters identification is a recently proposed technique and the methodologies that belong to it are usually termed *output-only*. They are particularly attractive owing to the wide range of applicability: e.g. to the cases when it is of paramount importance that the structure remain in-service and operating without disrupting the normal activities (e.g. transportation network) (Domaneschi et al, 2017; Sigurdardottir & Glišić, 2015).

Despite the number of SHM methodologies and the extensive literature with several applications, designers and owners relatively rarely employ SHM on real structures. In addition, the most effective SHM methodologies are usually restricted to specific conditions (type of structure, loading conditions, etc.). Furthermore, education in SHM, while expanding, is still limited.

This work is focused on the assessment of the modal characteristics of the Streicker Bridge on the Princeton University campus. An output-only method is applied to the response data in terms of longitudinal strains and curvature. The monitoring system consists in a fiber optic sensor network embedded in the footbridge concrete elements. The results are compared to previous outcomes from literature.

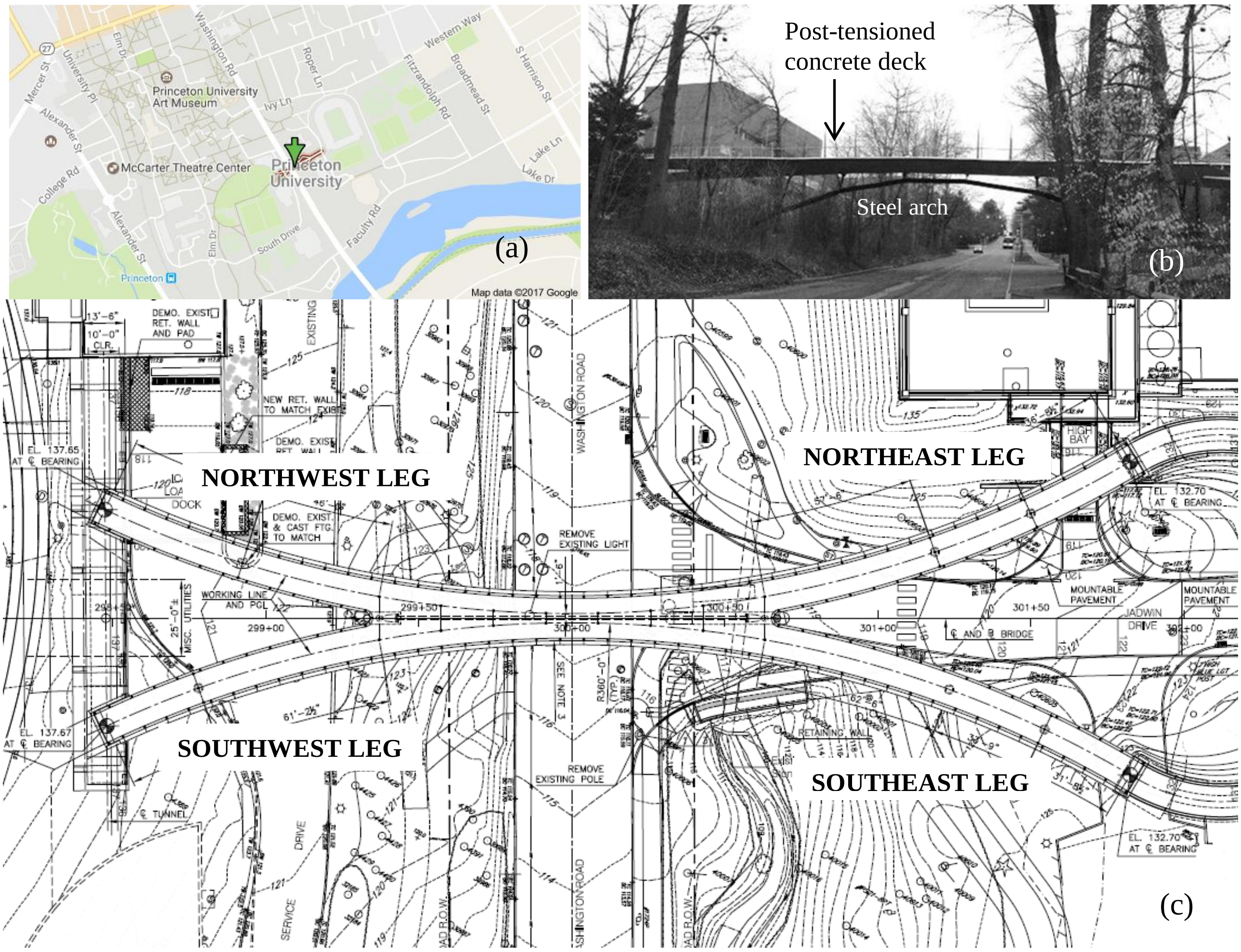

Figure 1. Streicker Bridge at the Princeton University: (a) location in the Campus, (b) image from Washington Road, (c) top view.

2. Streicker Bridge

Streicker Bridge is a 104-m long footbridge completed in 2010 on the Princeton University Campus overpassing Washington Road (Fig. 1a,b). The top view (Fig. 1c) of the bridge highlights a central main span and four lateral approaching legs. A steel arch supports the main span over Washington Road, while the deck is a post-tensioned high-performance concrete girder. There are also four post-tensioned high performance concrete lateral legs on the bridge which are supported by steel "Y" columns (Fig. 2). More details about the bridge can be found in (Sigurdardottir & Glišić 2015).

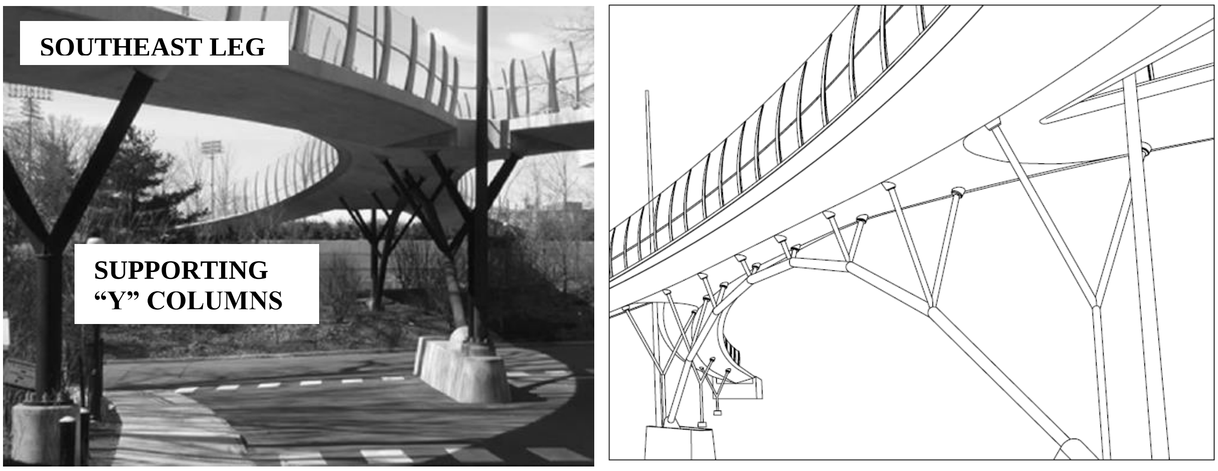

Figure 2. Details of steel columns under the East legs of the footbridge (a) and perspective view of the arch (b).

The legs connect the main span to the lateral bearings on the ground. The original shape in the horizontal plane provides horizontal stability to the footbridge despite the intrinsic slenderness of the steel supporting columns. Vertical stability is provided by the arch (Figure 2b) in the central main span and by the supporting columns under the legs. The width of the cross section increases from the middle of the main span to the connections with the legs which have a constant cross section. The maximum deck depth is 0.6 m and the cross-section diameter of the arch is 0.32 m.

3. The monitoring system

Previous research has demonstrated the capabilities of using long-gage strain sensors for the detection of local damage and for the assessment of the dynamic characteristics of a structure. In particular, fiber-optic sensors can show high sensitivity and measure beyond kilohertz frequency range. Furthermore, they can be employed in aggressive environments where they have proven stable and resistant to external perturbations such as chemical agents and environmental conditions (corrosion, electromagnetic interference, etc.).

Streicker Bridge is equipped with a series of fiber-optic strain and temperature sensors that provide the structure with an effective monitoring system. The bridge and the embedded monitoring system is frequently used for research and teaching on SHM. Because the bridge is rather symmetric in plan, only half of the main span and the longest leg (southeast) are equipped with the monitoring system.

Fiber-optic sensors were embedded in the concrete bridge deck during construction, providing monitoring of the structural response from the birth of the structure. Two types of fiber optic sensors were instrumented on the structure, discrete fiber Bragg-grating (FBG) long-gauge strain and temperature sensors and distributed Brillouin optical time domain analysis (BOTDA). For the purposes of this study, only the FBG sensors are used due to their ability to measure dynamic strain. Long gauge length of sensors is not sensitive to the local inhomogeneity that introduce discontinuities in the local mechanical properties of concrete.

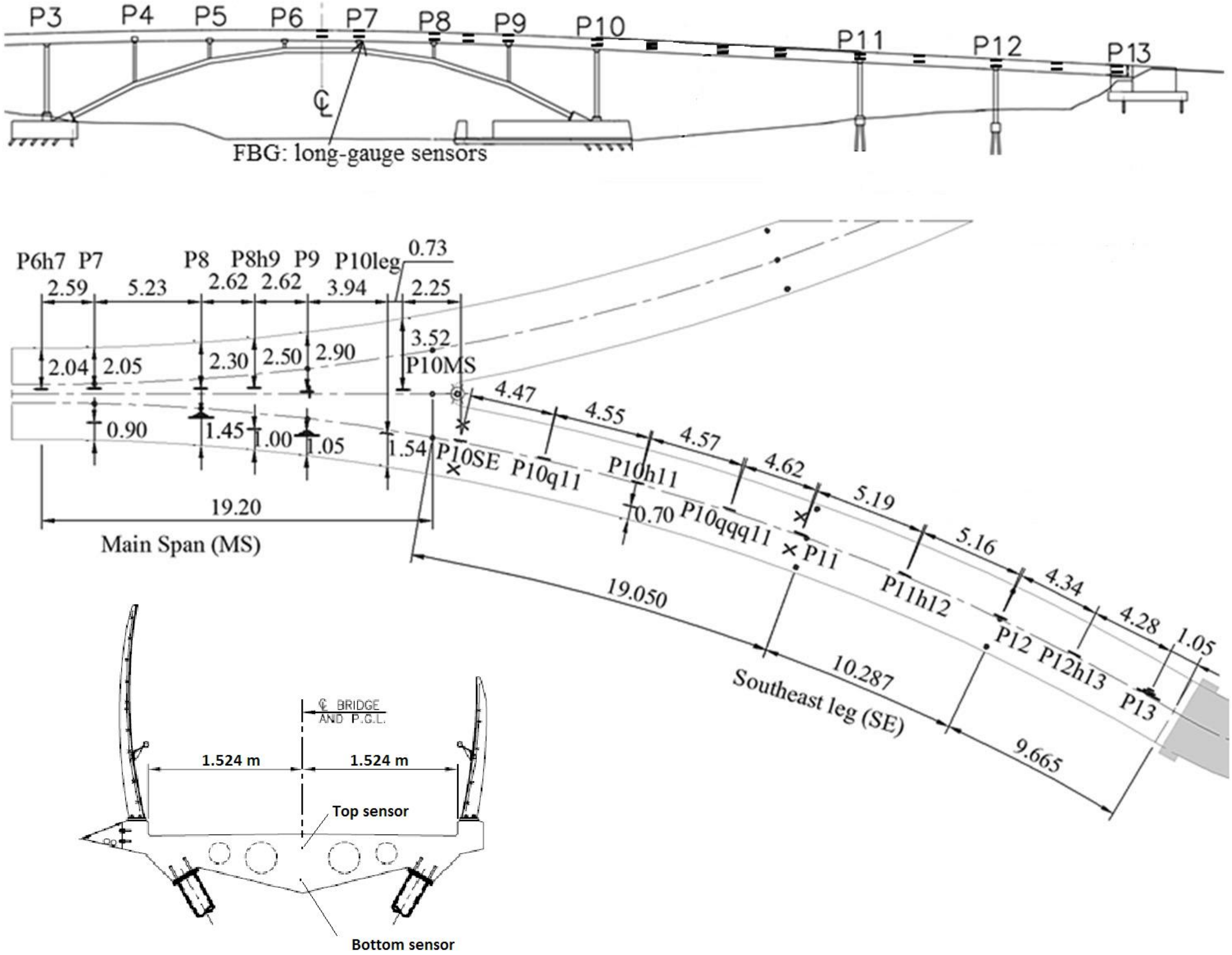

Figure 3. Sensors location on the deck and within the cross section (modified from Sigurdardottir and Glisic, 2015).

The monitored parameter in the bridge girder is the longitudinal strain and the derived parameter is the curvature (Domaneschi et al. 2017) that is determined from a couple of fiber optic sensors at the top and at the bottom of the cross section. During the dynamic tests on the structure, the strain measurements were recorded at a sampling rate of 250 Hz with an expected error in frequency of ± 0.06 Hz. Additional details on the specification of the monitoring system can be found in Sigurdardottir & Glišić (2015).

Figure 3 depicts the distribution of the discrete sensors on the bridge deck. The long-gauge FBG sensors are installed in different topologies. Only the parallel topology is considered in this work and it consists of two discrete sensors parallel to the longitudinal axis of the deck, approximately aligned with the vertical axis of symmetry, one sensor at the top and one at the bottom of the cross section. Parallel sensors capture strain due to normal force and bending moment that create axial strain in the cross section. Bending moment in particular creates curvature in the vertical plane. No significant shear or torsion forces are expected. Curvature χ can be calculated using available strain data at the top and the bottom of the cross section ($\varepsilon_{top}, \varepsilon_{bottom}$) as follows:

$$\chi = (\varepsilon_{bottom} - \varepsilon_{top})/h \tag{1}$$

where h is the vertical distance between the parallel sensors.

Every long-gauge FBG sensor is equipped with an FBG temperature sensor for temperature compensation and measurements. In (Sigurdardottir & Glišić 2015) additional details can be found for a more comprehensive description of the monitoring systems.
The main span of the footbridge is divided into seven segments between columns P3–P10 (see Figure 3). Parallel sensors are at columns P7, P8, P9, and P10 and at two locations mid-span between P6 and P7 (P6h7) and between P8 and P9 (P8h9). The southeast leg (three spans) is fixed to the deck of the main span at one end and simply supported at the other end, with sensors installed at columns P10-P12, at abutment P13, in the middle of each span (P10h11, P11h12 and P12h13) and in the quarters of the longest span (P10q11 and P10qqq11). The gauge length for the parallel sensors is set to 0.60 m, based on principles described in Glišić (2011).

4. Dynamic characteristics from literature

The footbridge has been extensively tested in several experimental campaigns. Furthermore, finite element (FE) simulations have been also performed with simple plane beam models. Therefore, literature data is available for comparison. In particular, the natural frequencies of the structure determined from the experimental tests were 3.11 and 3.72 Hz. On the other hand, the natural frequencies determined from the FEM model were equal to 3.21 and 3.77 Hz (Sigurdardottir & Glišić 2015). Vibration monitoring using a wireless MEMS accelerometer board is also reported in literature (Sabato 2015) and the modal frequencies are consistent with previous researches (3.08 Hz and 3.75 Hz). Table 1 summarizes the results from literature.

Table 1. Dynamic parameters from literature

	f_1 *[Hz]*	f_2 *[Hz]*
Experimental Tests (Sigurdardottir & Glišić 2015)	3.11	3.72
FEM (Sigurdardottir & Glišić 2015)	3.21	3.77
Experimental Tests (Sabato 2015)	3.08	3,75

All the reported results have been collected by employing group of pedestrians running or jumping at specific frequencies or randomly. The present study investigates the dynamic characteristics of the footbridge without knowing the characteristics of the input within an SHM output-only approach.

5. Results

The data currently available for analysis were collected in 2014. For the recorded sets of signals the input is unknown. The strains time histories from the parallel sensors are computed for obtaining the dynamic curvature (Equation 1). The curvature is computed for extracting modal properties of the footbridge. It has been verified that curvature processing allows halving the number of vectors to process without losing information from the strain data.
The experimental curvature data was processed in the frequency domain by computing the power spectral density (PSD) of the bridge response signals through the periodogram function. The PSD of a stationary random process is, by definition, a real symmetric function mathematically related to the autocorrelation sequence by the discrete-time Fourier transform. The periodogram is an

estimate of the PSD of a wide-sense stationary (weakly-stationary) random process, such as a finite-length segments of a signal.

Tests from 2014 were performed on the southeast leg of the bridge. The loading conditions are unknown, but they consisted of pedestrians that were jumping, running randomly over the bridge or marching at synchronized but unknown frequencies.
Figure 4 depicts the processed results from the set termed as *DynamicPeaks1* in the database in both the time and the frequency domain. Unfortunately some issues with the reading of sensors at P7 and P6h7 occur and data for those sensors were not available.
Figures 5 to 10 show the results in the frequency domain for all of the remaining data sets from the 2014 tests. Figure 5 also depicts an overview of the time history records for *DynamicPeaks1* data set. The sensors between P10-P12 are characterized by the highest intensity responses.

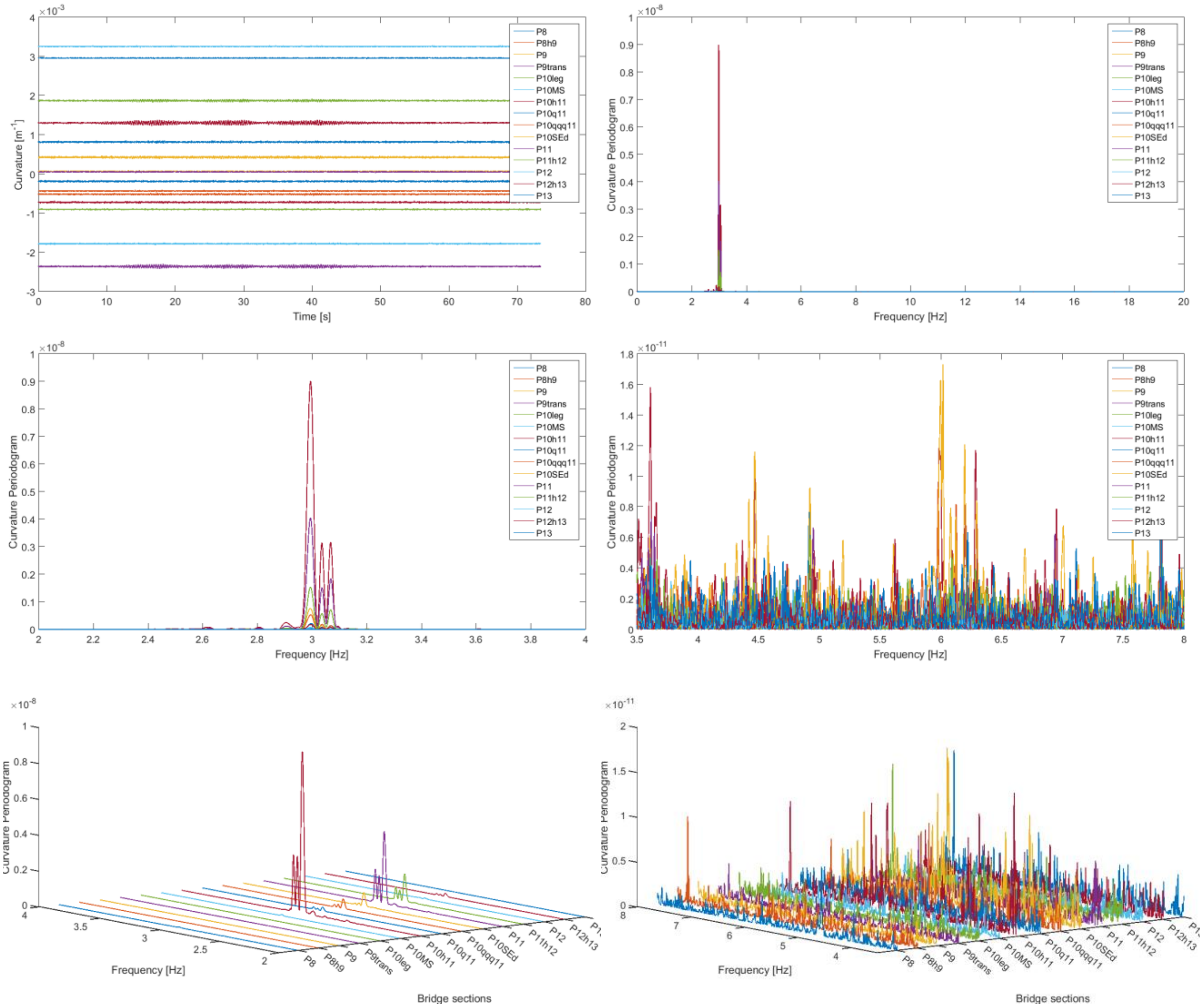

Figure 4. Processed results from the set termed as *DynamicPeaks1* in the database.

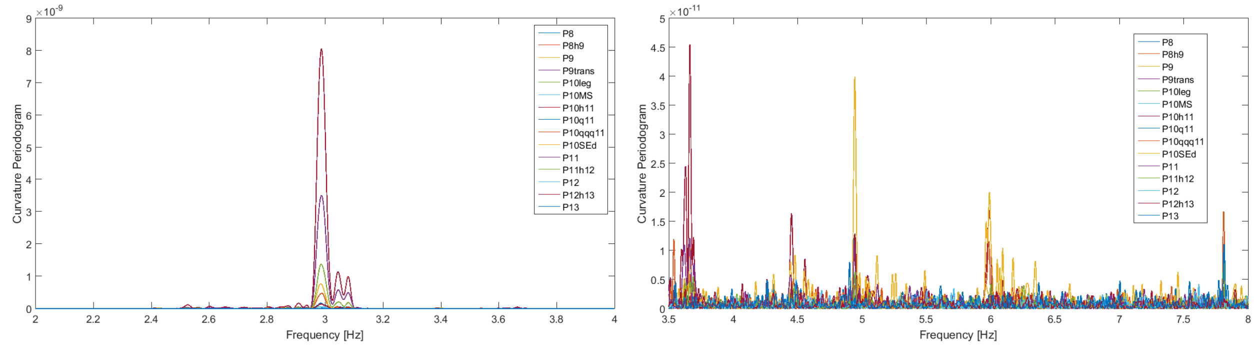

Figure 5. Processed results from the set termed as *DynamicPeaks2* in the database.

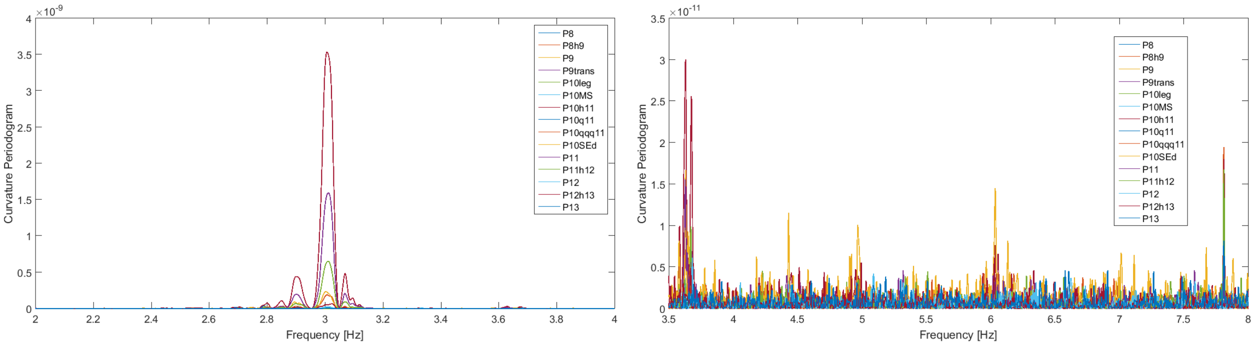

Figure 6. Processed results from the set termed as *DynamicPeaks3* in the database.

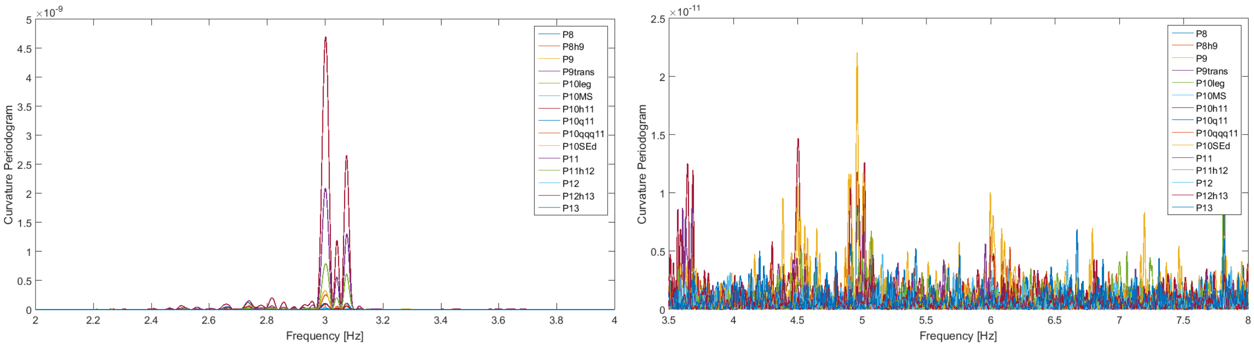

Figure 7. Processed results from the set termed as *DynamicPeaks4* in the database.

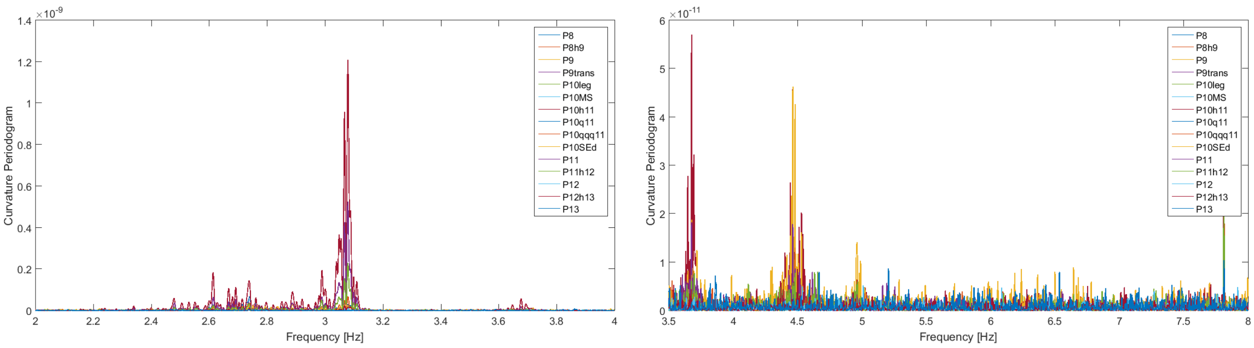

Figure 8. Processed results from the set termed as *RunningPeaks* in the database.

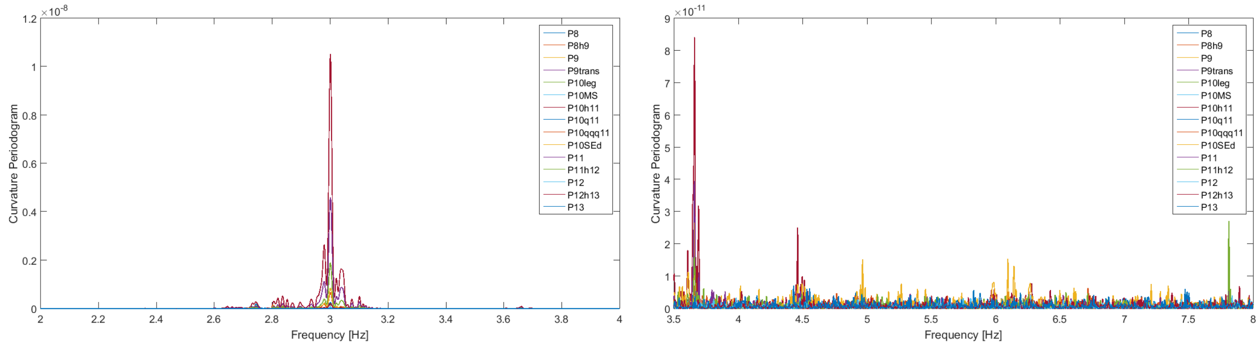

Figure 9. Processed results from the set termed as *DynamicPeaks41* in the database.

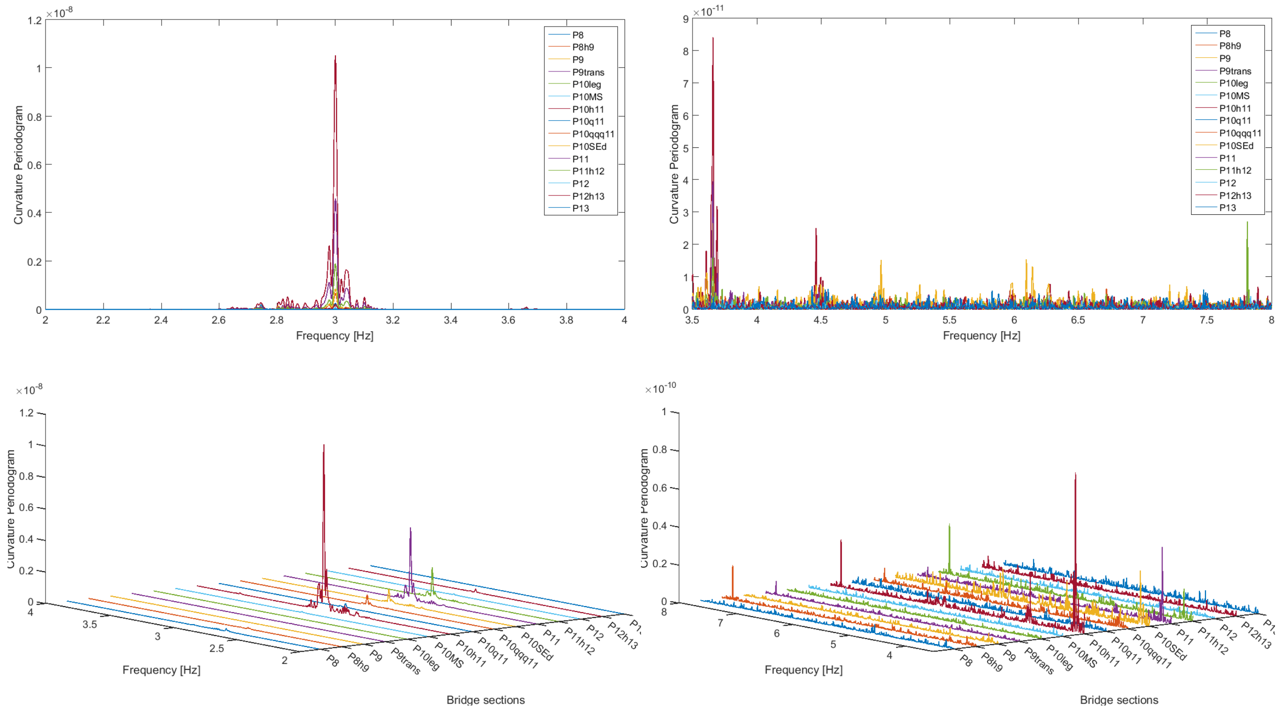

Figure 10. Processed results from the set termed as *DynamicPeaks42* in the database.

Table 2. Natural frequencies.

	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]	f_5 [Hz]	f_6 [Hz]
DynamicPeaks1	*2.94*	*3.61*	*4.47*	*4.92*	*6.01*	*7.81*
DynamicPeaks2	*2.98*	*3.66*	*4.45*	*4.94*	*5.99*	*7.81*
DynamicPeaks3	*3.00*	*3.63*	*4.43*	*4.96*	*6.03*	*7.81*
DynamicPeaks4	*3.00*	*3.64*	*4.50*	*4.96*	*5.99*	*7.81*
DynamicPeaks41	*3.00*	*3.66*	*4.46*	*4.96*	*6.09*	*7.80*
DynamicPeaks42	*2.99*	*3.68*	*4.42*	*4.94*	-	*7.81*
RunningPeaks	*3.08*	*3.67*	*4.46*	*4.96*	-	*7.81*

From these results, the first amplification peak in the frequency domain is determined to be approximately 3 Hz for all of the experimental tests. This is a lower value with respect to those from literature in Table 1. Also, the second peak has lower values (approximately 3.6 Hz). The available results in the range [3.5 Hz, 8 Hz] highlight a third peak around 4.4 Hz, a fourth at 4.9, a fifth one at 6 Hz and last one at 7.8 Hz. Table 2 summarizes the results of the analyses for each recorded signal.
Due to the location and topology of the embedded sensors, the recognized natural frequencies are reasonably associated to vertical flexural natural modes. Furthermore, comparable highlighted intensities in all data sets and the redundancy in the frequency values allow considering these outcomes accurate with satisfactory confidence.
The damping ratio of the first mode associated to 3 Hz natural frequency can be estimated by the applying the logarithmic decay formula at the sensor P10h11 and it is evaluated as 0.57%. This value, not reported by other research works in literature on the same footbridge, is compatible with others of similar slender structures (Shahabpoor et al., 2017; Van Nimmen et al, 2017).

6. Conclusions

This work investigates the modal characteristics of the existing footbridge on the Princeton University campus in Princeton US, the Streicker Bridge. The investigation uses measurements collected by long-gauge fiber optic strain sensors embedded along the entire structure. The power spectral density of the distributed long-gauge dynamic curvature is used. The damping ratio associated to the first identified mode is also computed.
Pedestrian loading represents the external excitation. However, detailed information on the load intensity, frequency and distribution are lacking and the research can be ascribed within the *output-only* procedures. Comparison with previous works from literature mostly validate the proposed procedure, as slightly lower frequency values have were noted.
The present investigation represents the first step in further research for consolidating the results and deepening the knowledge on the footbridge characteristics.

Acknowledgements

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